ANALYSIS AND SIMULATION OF AUTOMATED VEHICLE STATIONS

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ABSTRACT

A variety of stations for automated-vehicle systems are analyzed and compared. These cover a spectrum from on-line stations for systems that operate like CRT systems on the one hand, to GRT and High Capacity PRT stations on the other. Most of the analysis is directed toward off-line stations for multiparty vehicles. The geometric design of off-line ramps is discussed, and the operation of long headway (>30 sec) on- and off-line stations is analyzed with the aid of time-space diagrams. Simulation results are given for GRT off-line stations with entrance and exit vehicle queues, and two station-simulation computer programs are described. Passenger handling strategies for GRT stations are discussed including some of the inherent problems resulting from a multi stop, demand-activated network operating policy. Comparisons are made among station types in terms of time lost per stop, ease of passenger handling, off-line ramp length, and vehicle and passenger throughput.

It is concluded that both the all-stop, scheduled system with on-line stations and the HCPRT system that provides non-stop, origin-to-destination, single-party service are promising alternatives. The GRT, demand-activated, multi-party, multi-stop type of operating policy seems to offer few operational advantages and many disadvantages compared to using similar automated vehicles in conventional, scheduled operation.

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1. Introduction

There is an almost continuous spectrum of possible exclusive-guideway, automated-vehicle systems, ranging from long headway CRT-like systems at one extreme to fractional-second-headway High Capacity PRT (HCPRT) systems at the other. This paper examines station designs and station operating policies that are appropriate to different points along the spectrum of operational headways. No attempt will be made to cover every possible station layout for a given headway; in particular stations with multiple off-line ramps or with lateral docking are not treated. Rather, a specific station design will be analyzed for each headway range, and finally the different station types will be compared. The station types are shown in Figure 1, along with the corresponding mainline headway range.

The results to be presented for Group Rapid Transit (GRT) off-line stations are based on two detailed simulation computer programs, one developed by the authors, and one by S & A Systems (1). A brief description of these programs is given in Appendices A and B. Stations for High Capacity PRT systems will not be discussed in detail, as they have been dealt with extensively in the literature (2-4).

2. Geometric Design of Off-line Stations

For all systems, regardless of headway, the geometry of off-line station guideway is primarily determined by:

- Passenger acceleration and jerk limits
- Vehicle speed at diverge and merge switches
- Whether or not longitudinal acceleration is combined with lateral
- Vehicle length and spacing between vehicles
- Number of queue and platform positions

The passenger acceleration and jerk limits are affected by whether all seated passengers are assumed or if standees are allowed. Even within these categories there is disagreement as to the proper values (3-8). The values used in all the following analyses are:

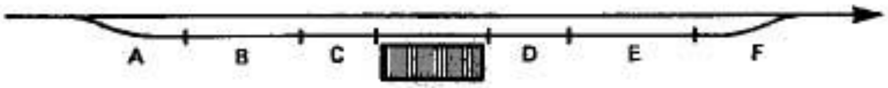
	Standees Allowed		All Seated	
	m/s^2, m/s^3	ft/s^2, ft/s^3	m/s^2, m/s^3	ft/s^2, ft/s^3
Longitudinal Acceleration	1.2	4.0	2.4	8.0
Longitudinal Jerk	0.9	3.0	1.8	6.0
Lateral Acceleration	1.2	4.0	1.8	6.0
Lateral Jerk	0.9	3.0	1.2	4.0

a) On -Line
60+ Second Headway

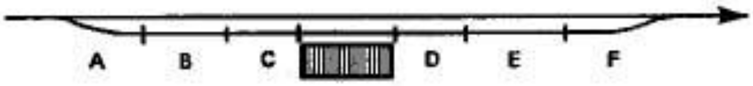
A. SWITCH
B. DECELERATION LANE
C. ENTRANCE QUEUE
D. EXIT QUEUE
E. ACCELERATION LANE
F. SWITCH

b) Simple Off-Line
30-45 Second Headway

c) Flip-Flop
30-45 Second Headway



d) GRT
3-15 Second Headway



e) PRT
0.5-2 Second Headway

▥ PLATFORM

Figure 1. Spectrum of Automated Vehicle Stations

The advantages of an all-seated policy include shorter off-line ramp lengths, somewhat greater vehicle throughput due to reduced movement times within the station, and slightly reduced origin-to-destination travel times. It is not clear whether it is possible to design a multi-party vehicle on the assumption of all-seated passengers. A design that would minimize the possibility of standees (for example an airport limousine) would also make it difficult and time consuming for passengers who weren't next to the vehicle door to exit during intermediate stops. One possible method of achieving multi-party, all-seated operation is to run vehicles non-stop from origin to destination (or to a transfer station) to ensure that all parties deboard simultaneously.

The speed of vehicles at diverge and merge switches can affect station length even more strongly than seating policy. A high speed results in a long station, while decelerating before the station and accelerating after it on the main line causes two difficulties: 1) vehicles which bypass the station may be slowed down if the vehicle ahead of them is entering, and 2) during on-line deceleration vehicles close on one another so that the effective headway for collision-avoidance purposes is reduced. This second effect occurs because all vehicles must start decelerating at approximately the same point on the main line, and a vehicle will continue to travel at line speed for one operational headway while the vehicle ahead of it is slowing down. Therefore, while the operational headway, which is just the time difference between two vehicles passing the same point, will remain constant, the "compressed" headway, which is given by

$$\frac{\text{Distance from the front of lead vehicle to the front of trailing vehicle}}{\text{Speed of trailing vehicle}}$$

will be reduced. This will increase the requirements on the control system.

The combination of longitudinal and lateral acceleration, i.e., changing speed through the switch, offers the possibility of reduced off-line length. This type of operation poses the same problems with compressed headway as does on-line deceleration, and in the analysis to follow, longitudinal and lateral accelerations are combined only in stations for long (>30 sec) operational headway systems where a great deal of headway compression can be tolerated. If acceleration and jerk in two directions are to be combined it is desirable to keep the vector sum within passenger comfort limits. Since the lateral and longitudinal limits for standees are the same, the individual limits can simply be divided by $\sqrt{2}$. (9).

The spacing between vehicles in queue areas and at platform berths is a subject surrounded by controversy. A close spacing (say less than 3m or 10ft) almost certainly means that a "stopping distance" operating policy* will have to be abandoned. The station design to be analyzed will in most cases assume a 1.5 m (5 ft) spacing between vehicles inasmuch as the Morgantown system currently uses a 1.2 m (4 ft) spacing.

The formulas used to calculate station-element geometries and times for

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* A stopping distance policy (10,11) is usually taken to mean that under worst-case conditions including instantaneous stopping of a vehicle and simultaneous motor overrun of a trailing vehicle, no collision will occur.

vehicle maneuvers are given in Table l. The two equations for each distance or time correspond to the two separate cases that arise depending on whether or not acceleration reaches its maximum value. For example the switch-length equations correspond to two different switch geometries. If the sidestep distance, H, is less than $2A^3/J^2$, then the geometry consists of 4 spirals (12). If H is greater than $2A^3/J^2$, the geometry is: spiral, circular arc, spiral, spiral, circular arc, and spiral. The spirals are defined by the jerk limits while the circular arcs are defined by the acceleration limits. It is common practice when designing switches for steel-wheel/steel-rail technology to insert a straight section between the middle two spirals of a switch. The formulas in Table 1 do not take this into account.

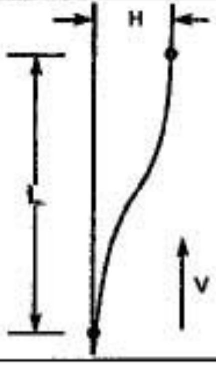
3. Stations for Long-Headway Systems

Three station designs that are suitable for headways of from 30-60 seconds are shown in Figure la, b, and c. The on-line station shown in Figure la can be used with mainline headways of approximately 60 seconds or greater. The simple off-line station (Figure lb) is assumed to have space for just one train on the off-line, with the relatively long headways permitting most of the deceleration and acceleration to occur on the main line. Express trains would bypass this type of station if local and express service were provided. The flip-flop station is similar to the simple off-line station, except in the flip-flop the platform is between the main line and the off-line. One possible operating strategy with this kind of station would be an all-stop policy in which alternate trains stop at alternate sides of the station (13) - hence the name. In addition, the flip-flop station could be used in conjunction with the simple off-line station if a local and express network operating policy were desired. The express trains would then stop on the straight side of the flip-flop stations. These three station types - on-line, simple off-line, and flip-flop - can all be implemented with conventional technology including a fixed block control system and open-loop brakes. The control system sophistication is determined not by the operational headway but rather the minimum compressed headway discussed earlier. All of these stations are suitable for control systems that allow a minimum compressed headway of approximately 15 seconds. If a stopping-distance policy is to be followed, this implies a guaranteed emergency deceleration rate of about 1.5 m/sec^2 (5 ft/sec^2), a control response time of 2 seconds and a block length of approximately 8 m (26 ft).

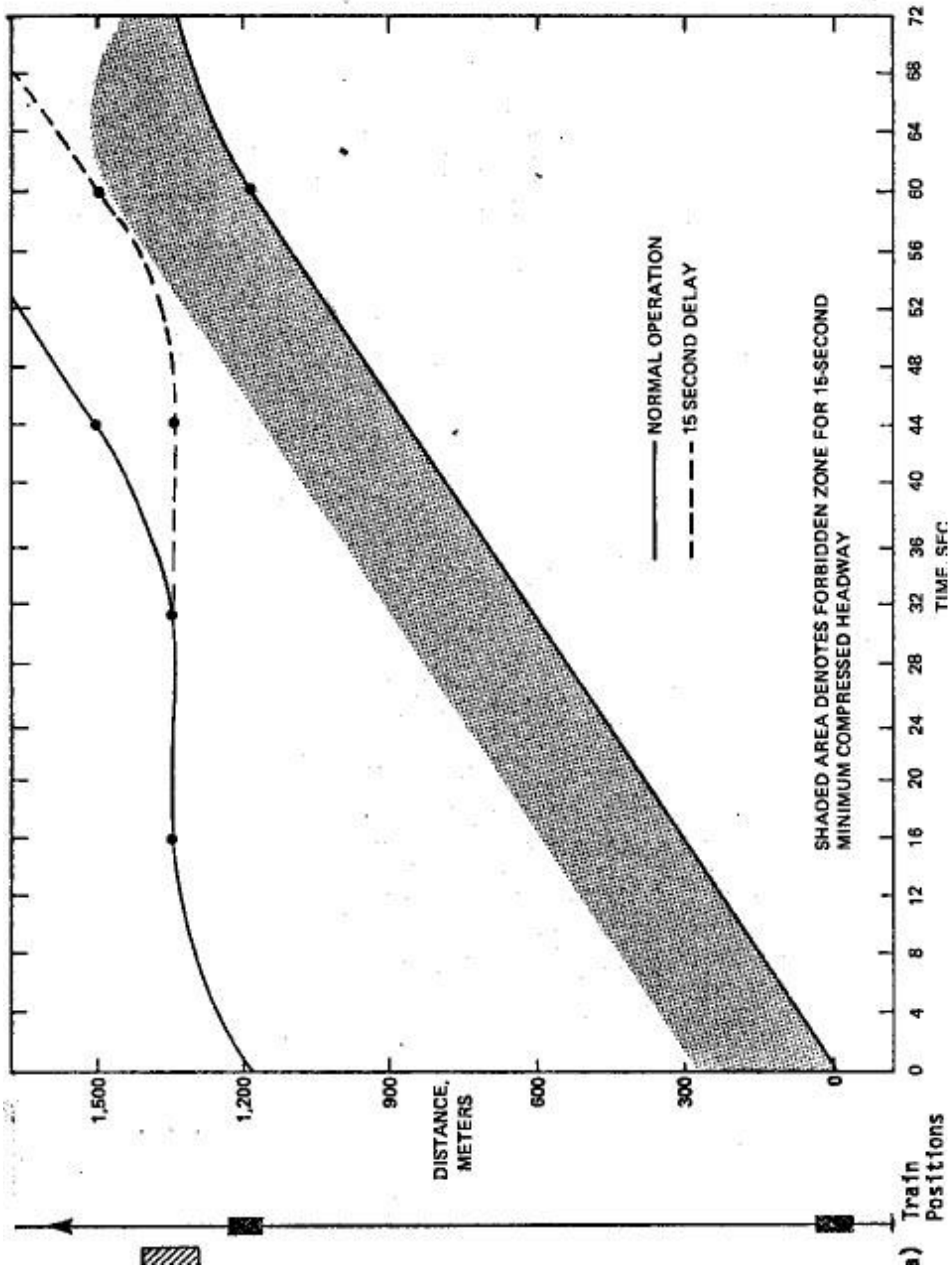
3.1 On-line Station

The operation of an on-line station can be understood with the aid of the time-space diagram shown in Figure 2. Time flows from left to right while trains move from bottom to top. Each train thus traces out a curve whose slope is proportional to speed. Figure 2a is a scale drawing of the situation at Time = 0. It is assumed two trains are approaching the station 60 seconds apart at 20 m/s (66 ft/s, 45 MPH). This corresponds to a distance separation (ignoring train length) of 1200 m (4000 ft). The lead train decelerates to a stop in 17 seconds, dwells for 15 seconds, and accelerates to 20 m/s (66 ft/s, 45 MPH) in an additional 17 seconds. Meanwhile the second train is approaching the station at a constant 20 m/s (66 ft/s, 45 MPH). If the first train leaves on schedule, the minimum separation between trains will be 520 m (1700 ft). Since the minimum compressed headway is 15 seconds, this means the lead train can be delayed by 11 seconds (the dashed line in Figure 2b) without interfering with the second train. It would also be possible to reduce the operational headway to 49 sec.

Table 1. Basic Equations for Station Design and Analysis

Maneuver or Station Element	Equations*
Speed change between V_1 and V_2 on straight guideway where $V_2 > V_1$ Acceleration = 0 at beginning and end of maneuver	Time Required, T — Distance Required, D $T = 2\sqrt{\frac{V_2 - V_1}{J}}$ — $D = (V_1 + V_2)\sqrt{\frac{V_2 - V_1}{J}}$ if $V_2 - V_1 \leq \frac{A^2}{J}$ $T = \frac{V_2 - V_1}{A} + \frac{A}{J}$ — $D = \frac{V_2^2 - V_1^2}{2A} + \frac{A(V_1 + V_2)}{2J}$ if $V_2 - V_1 \geq \frac{A^2}{J}$
Constant-speed switch between two parallel lines a distance H apart. Equations are exact only if the component of velocity parallel to the main line remains constant while traversing switch	 Switch Length, L $L = V\left(\frac{32H}{J}\right)^{1/3}$ if $H \leq \frac{2A^3}{J^2}$ $L = V\left[\frac{A}{J} + \sqrt{\frac{A^2}{J^2} + \frac{4H}{A}}\right]$ if $H \geq \frac{2A^3}{J^2}$
Position change of distance H. Speed and Acceleration = 0 at beginning and end of maneuver	Time Required, T $T = \left(\frac{32H}{J}\right)^{1/3}$ if $H < \frac{2A^3}{J^2}$ $T = \frac{A}{J} + \sqrt{\frac{A^2}{J^2} + \frac{4H}{A}}$ if $H \geq \frac{2A^3}{J^2}$

*Acceleration limited to A, jerk limited to J.


NORMAL OPERATION
15 SECOND DELAY
SHADED AREA DENOTES FORBIDDEN ZONE FOR 15-SECOND MINIMUM COMPRESSED HEADWAY
DISTANCE, METERS
0
300
600
900
1,200
1,500
TIME, SEC
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
a)
Train Positions

but this would eliminate all slack in the system, and any delay in one train would be transmitted to all following trains in a shockwave effect.

3.2 Simple Off-line Station

There is a trade off between the length of a simple off-line station and the time lost in passing through the off-line guideway. A very short station will require an abrupt switch that must be negotiated slowly, wasting time. Figure 3a shows a simple off-line station layout that provides a compromise between length and travel time. The off-line is composed of two four-spiral switches plus a 5 m (16 ft) straight section. This particular station was designed for a train length of 29 m (95 ft); if longer trains are required the straight off-line section can simply be lengthened. The speed profile of a train entering this station is shown in Figure 3b. The train first decelerates on-line, from 20 m/s (66 ft/s, 45 MPH) to 7.6 m/s (25 ft/s, 17 MPH) at 1.2 m/s^2 (4.0 ft/s^2). When the front of the train enters the switch, the speed is held constant for 3 seconds, and then the train decelerates to a stop at 0.9 m/s^2 (2.8 ft/s^2). After a dwell of 15 seconds, this process is repeated in reverse when the train leaves the station. This deceleration, dwell, and acceleration results in a time loss of 41 seconds compared with bypassing the station at a constant 20 m/s (66 ft/s, 45 MPH). A time-space diagram for the operation of a simple off-line station is shown in Figure 4. It is assumed every other train is an express that bypasses the station. The dotted portion of the local train line indicates those times it is clear of the mainline. It is necessary to extend the local trains' dwell time an extra 5 seconds to allow the express train to pass without violating the minimum compressed headway of 15 seconds. This increases the time lost in stopping at the station to 46 seconds. The next train after the express is another local that will enter the same station. It is assumed the second local follows the express by 40 seconds that allows the first local to increase its dwell time to 30 seconds (dashed line in Figure 4) without delaying any other train. This scheduling results in an average headway between all trains of 35 seconds.

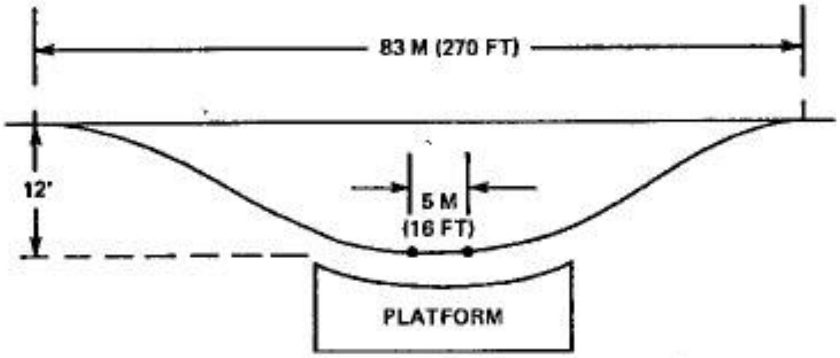
3.3 Flip-Flop Station

With all-stop operation, the flip-flop station shown in Figure lc has almost twice the capacity in trains per hour as an on-line station. This results in trains and platforms only half as long, and the greater frequency of service allows a large number of different service routes in the network that will reduce transfers. In addition the flip-flop station can be operated as a simple off-line station with the straight side serving as a bypass track.

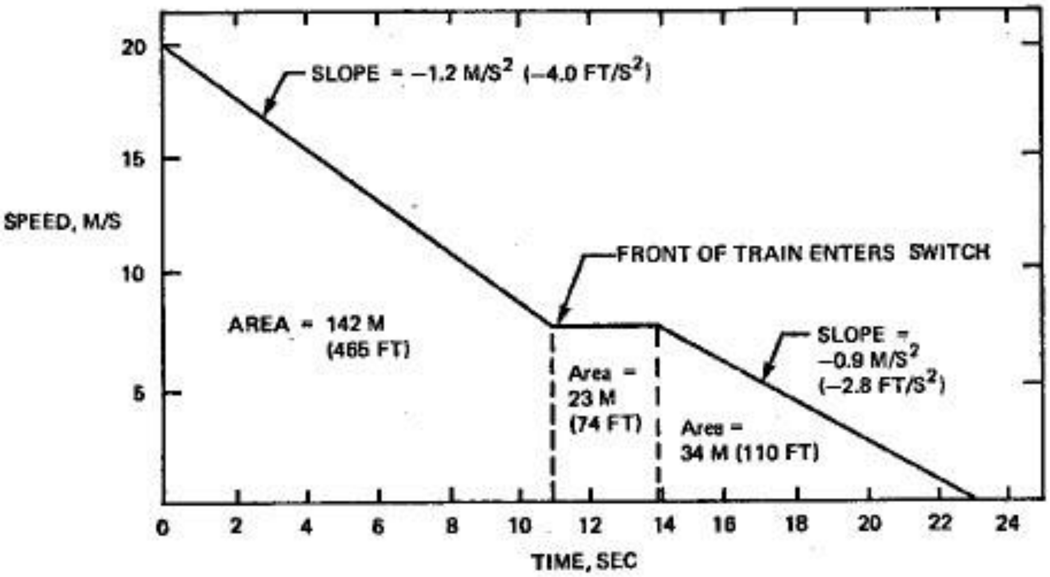
The geometry of a flip-flop station is similar to that of a simple off-line station except that the greater sidestep distance requires a longer off-line. For a platform 7 m (25 ft) wide at the middle, tapering to 4.6 m (15 ft) at the ends, the off-line length would be approximately 140 m (450 ft). With this station geometry, the time lost in stopping on the curved side of the station would be about 46 seconds.

4. GRT Off-line Stations

The GRT off-line station with queues shown in Figure ld requires a step forward in control technology, in part because of the relatively close vehicle



a) Geometry



b) Speed Profile for Train Entering Off-Line

Figure 3. Layout and Operation of a Simple Off-Line Station

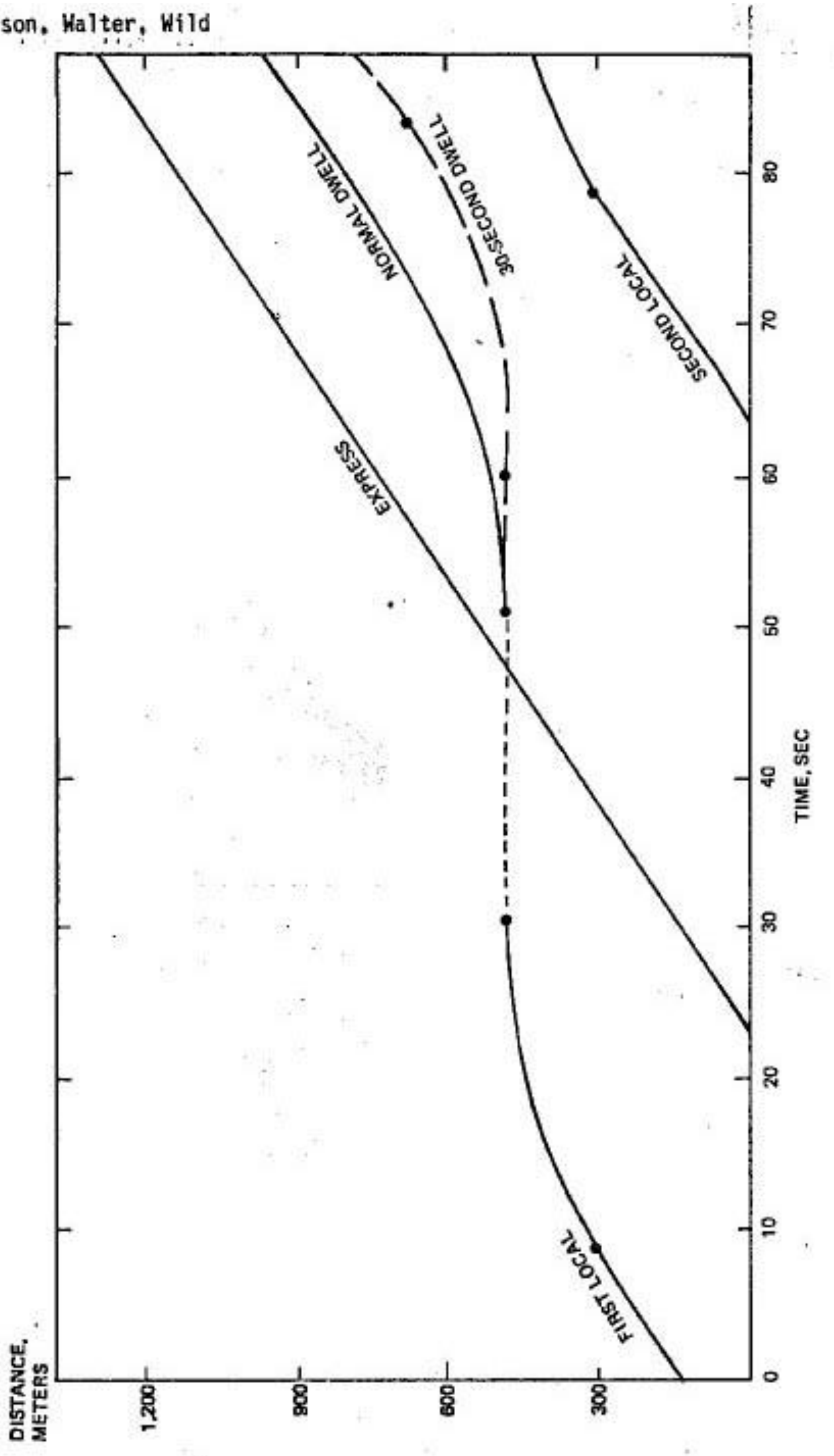


Figure 4. Time-space Diagram of Trains Entering and Bypassing a Simple Off-Line Station

spacing within the station. One possible network operating policy with this type of station would use one or two vehicle trains with nominally scheduled routes. This would involve a large number of separate routes and separate trains that could probably not be held to a rigid schedule, hence the vehicle queues. If the system were demand activated this would further increase the stochastic nature of network operation. The length of this type of station is assumed to be given by:

2* (switch length for 11 m/sec (25 MPH)) +
2* (deceleration ramp length 11 m/sec → 0) +
N* (Vehicle length) + (N-l) * (Vehicle spacing)

where N is the sum of entrance queue, platform and exit queue positions. An 11 m/sec (25 MPH) diverge and merge speed and a constant speed through the switches was used since the shorter operational headways allow less on-line deceleration than in the case of stations for long-headway systems.

4.1 Passenger Handling in GRT Stations

The on-line and simple off-line stations discussed earlier are easy for passengers to use in that trains arrive one at a time, at least 60 seconds apart. If the flip-flop station is used in combination with simple off-line stations to run local and express service, an additional complexity is introduced, but passenger handling should still remain fairly simple. GRT station operation in an all-scheduled mode represents a further step up in complexity since several separate vehicles can arrive simultaneously, each with different destinations. In addition, the number of service routes with such a system would probably be so great that it would be necessary for passengers to indicate their destinations and be given the number of a particular vehicle to board. A demand-activated GRT system with a multi-stop operating policy poses by far the most severe passenger handling problems. A large station might have 5 or 6 vehicle berths, and in general it will not be possible to predict the berth at which a vehicle will stop. This is because to keep waiting times reasonably short a passenger must be able to call into the station a vehicle which happens to be just upstream of the diverge switch. If this vehicle is switched into the station, those vehicles that were previously destined to enter the station will be "bumped" back one platform position. Thus, a passenger will not know his vehicle's berth number until the vehicle is in the station. This gives him about 30 seconds to reach the correct berth. This would prove difficult for aged or handicapped passengers. There are other complications that appear with a multi-stop GRT operating policy, although their nature depends on whether an all seated policy is assumed or standees are allowed. If the interior is designed to discourage standees, passengers far from the vehicle doors who want to deboard will have to climb over those next to the door. If on the other hand the vehicle is designed to permit standees another complication appears. Vehicles will not have a fixed capacity; instead the capacity will depend on the willingness of the passengers to accept crowding. Unless very conservative loading standards are used, passengers who are assigned to a vehicle may be left behind because of unwillingness to crowd on board.

A great simplification in passenger handling is achieved if all passengers deboard whenever a vehicle arrives at a station platform. This can be achieved by providing non-stop O-D service between pairs of stations with high demand, while requiring transfers rather than stops en route when travelling between low-demand pairs. With this policy all vehicles are identical (since they become empty) when they arrive at a station platform, so it becomes possible to tell a passenger well in advance which berth he will use.

In a HCPRT system where non-stop, origin-to-destination, single-party service is always provided, passenger handling is relatively simple. A passenger must still indicate his destination, but he is free to board any vehicle at any berth.

4.2 GRT Off-line Station Simulation Results

A number of experiments were run with the GRT off-line station simulation model described in Appendix A. The basic question all simulation experiments were designed to answer is: How many vehicles and how many passengers per hour can a given station handle? A measure of the performance of a randomly operated off-line station is its rejection rate. If it is assumed that vehicles cannot stop on the mainline, then situations will occur in which vehicles that should enter the station will be denied service. This is extremely undesirable, and the rejection rate should probably be held to less than ½ of one percent.

A number of assumptions were made concerning the operation of GRT off-line stations. Some of these are:

- Vehicles follow precalculated speed profiles when moving within the station. Since vehicles do not "follow" one another, the simulation model must plan vehicle movements so that a 1.5 m (5 ft) spacing between vehicles is maintained.
- All vehicles have a fixed capacity even though standees are allowed.
- The spatial movement of passengers within the station is not modelled.
- Vehicle dwell time at the platform is given by:

  Dwell time = 5.63 + N * (1.13 + 0.4 * XN0RM) seconds

  where: N is the sum of boarding and deboarding passengers

  XN0RM is a normally distributed random number with mean of 0 and standard deviation of 1.

  If the above expression gave a value of less than 15 seconds, the dwell time was set to 15 seconds. The expression was determined experimentally at the Airtrans system at the Dallas-Fort Worth airport.
- When several passengers are waiting for the same vehicle, they will queue first in, first out. This may be difficult to implement in practice.
- Passengers arrive in parties of from one to five passengers the party size distribution is:

Party Size	Fraction of Parties
1	.92
2	.05
3	.01
4	.01
5	.01

This yields an average party size of 1.14

- Party arrival is a Poisson process.

Table 2 presents the results of GRT-station simulation experiments with 12 passenger vehicles. The column “Average Vehicle Arrival Rate” gives the number of vehicles passing through the off-line guideway per hour, while “Average Passenger Arrival Rate” is the number of passengers boarding vehicles per hour. It was assumed that no passengers deboarded. The numbers in the configuration column refer to entrance queue, platform, and exit queue positions in that order. The average passenger wait times ranged from 40 to 100 seconds, but these values are dependent on the assumption of 12 scheduled routes serving the station with passenger demand divided equally among the routes. It can be seen from Table 2 that mainline Volume/Capacity ratio seems to have little effect on station performance.

Each row in Table 2 is the average of three separate runs of one hour each, with a different seed being used for the simulation model’s random number generator for each run. This limited amount of simulation means there is probably an uncertainty of at least several tenths of one percent in the rejection rates, and in some cases stochastic effects cause small stations to appear better than larger ones. Based on the results in Table 2 and a theoretical analysis of exit queue operation (14), the following station configurations should provide a rejection rate of less than 0.5 percent, assuming that on the average fewer than ten passengers board each vehicle:

Less than 300 vehicles/hour	6/3/4
300-400 vehicles/hour	7/4/5
400-500 vehicles/hour	9/5/6

Figure 5 shows the results of another set of simulation experiments, this time with 40 passenger vehicles. The station configuration was fixed at 4/2/2 and the vehicle and passenger arrival rates were varied. The number of vehicles entering the off-line ranged from 120 to 210 per hour while the passenger arrival rate was defined indirectly by letting the average sum of passengers boarding and deboarding each vehicle vary from 2 to 24. Two thirds of these passengers were assumed to board vehicles while one-third deboarded. Each point in Figure 5 represents the average of four separate simulation runs of four hours each. Because each experiment involved only 2000 to 3000 vehicles, rejection rates of less than 0.1 percent are not statistically significant. If a rejection rate of less then 0.5 percent is desired, a number of different combinations of vehicle and passenger flows are possible:

- If on the average a total of 16 passengers board and deboard each vehicle, 140 vehicles per hour can pass through the station for a total of approximately 2200 passengers per hour

Table 2. GRT Station Simulation Experiments with 12-Passenger Vehicles

AVERAGE VEHICLE ARRIVAL RATE (VEHICLES/HR)	AVERAGE PASSENGER ARRIVAL RATE (PASSENGERS/HR)	MAINLINE VOLUME TO CAPACITY RATIO	CONFIGURATION ENT Q/PLAT/EX Q	PERCENT OF VEHICLES REJECTED
300	600	0.70	6/3/3	0.0
		0.85	4/3/3	1.3
		0.85	5/3/3	0.3
		0.85	6/3/3	0.0
	2,100	0.85	6/3/4	1.5
	2,400	0.70	6/3/3	0.0
		0.70	7/3/4	0.7
		0.85	6/3/3	1.0
		0.85	7/3/4	0.3
		1.00	6/3/4	0.3
		1.00	7/3/4	0.7
400	800	0.70	6/3/4	0.5
		0.85	6/3/3	0.5
		0.85	6/3/4	0.3
		0.85	5/4/4	2.0
		1.00	6/3/4	1.5
	3,200	0.70	7/4/4	0.0
		0.85	6/4/4	1.0
		0.85	7/4/4	0.3
506	1,012	0.70	6/4/4	0.0
		0.85	6/4/4	0.0
		0.85	7/4/4	0.0
	2,024	0.70	7/4/4	0.1
		0.85	6/4/4	0.4
		0.85	7/4/4	0.2
	4,048	0.70	9/5/5	0.0
		0.85	9/5/5	0.0
		0.85	10/5/5	0.0
	5,060	0.85	9/5/5	0.2
		0.85	10/5/5	0.4
533	1,066	0.90	7/4/5	0.0
	2,132	0.90	7/4/5	2.0

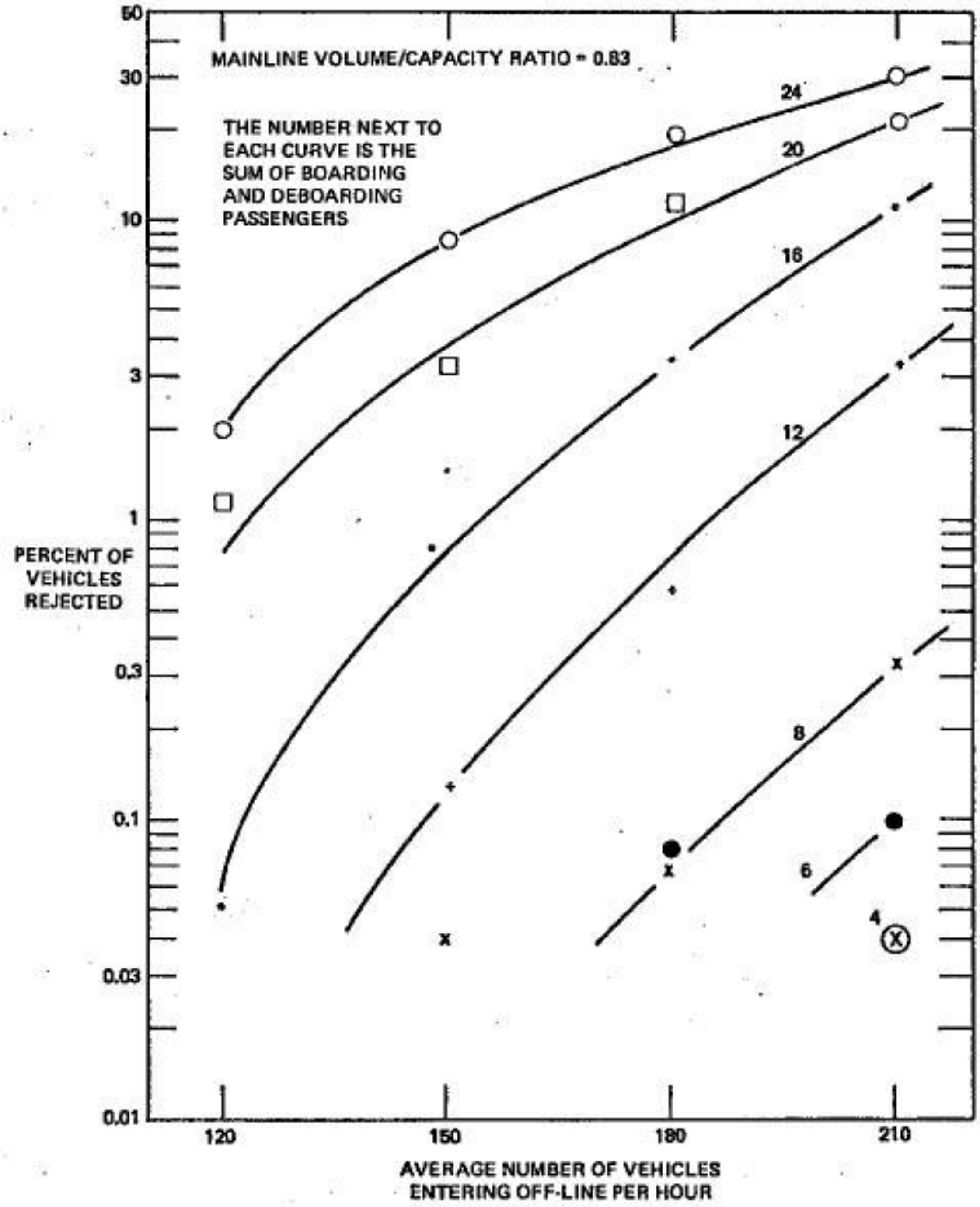


Figure 5. Performance of 4/2/2 Station with 40-Passenger Vehicles

- with 12 passengers boarding and deboarding each vehicle, 160 vehicles give 2000 passengers per hour
- with 8 passengers per vehicle, 210 vehicles give about 1700 passengers per hour.

Since the same size vehicle could be used with on-line stations in an all-stop type of operation, a significant parameter is the average time lost in stopping at a 4/2/2 station. This parameter varied from 60 to 90 seconds compared with about 34 seconds for an on-line station with a line speed of 20 m/s (66 ft/s, 45 MPH).

All of the above simulation experiments used the model described in Appendix A and assumed a 1.5 m (5 ft) spacing between vehicles, which for any practical control system would violate a stopping-distance operating policy. Another set of station-simulation experiments was run by S&A Systems (1) of Dallas, Texas in which the control system was modelled in great detail and a stopping distance policy was observed. These experiments used the computer model described in Appendix B and a curve of minimum vehicle spacing vs. speed containing the following Points:

Speed of Trailing Vehicle			Minimum Spacing	
m/s	ft/s	MPH	m	ft
0	0	0	3.7	12
3.0	10	6.8	9.2	30
6.1	20	13.6	19.2	63
9.1	30	20.4	33.0	108

The overall conclusion of these experiments was that a stopping-distance operating policy based on the above spacing will reduce vehicle throughput for a given station configuration by approximately 35 percent.

5. Comparisons and Conclusions

Table 3 compares those station characteristics that are more or less independent of network geometry. An especially important characteristic is the Time Lost in Stopping. This is generally 35 seconds or less in a scheduled, on-line system, but can be 2 or 3 times as great for a stochastically operated station with queues. This leads to the conclusion that a few intermediate stops in a GRT system are enough to wipe out the travel time savings compared with an on-line, all-stop system.

The flip-flop station, if operated in an all-stop mode, will result in slightly more time lost per stop than the on-line station. A combination of flip-flop and off-line stations would allow local and express service, but the overall time savings for any practical network would be small.

The overall conclusion is that either an on-line, all-stop system or a HCPRT system with non-stop, single-party origin-to-destination service are promising alternatives, whereas the intermediate headway systems (including GRT) offer little, if any, improvement in service over a simple on-line all-stop system. A system such as the High Performance PRT with 12 passenger vehicles might be desirable if operated as a HCPRT during the off-peak and if used to provide multi-party, non-stop origin-to-destination (or to transfer station) service during peak periods.

Table 3. Comparison of Automated Vehicle Stations

System Type	All Stop	Skip Stop		GRT				HCPRT
Station Type[1]	On-Line	Flip Flop	Simple Off-Line	4/2/2	6/3/4	7/4/5	9/5/6	
Headway Range (sec)	60+	30–45	30–45	3–15				0.5–2
Trains/Hour/Direction	60	110	60	N/A				N/A
Vehicles/Hour/Direction[2]	N/A	N/A	N/A	200	300	400	500	Note 4
Time Lost per Stop (sec)	34	34–46	41	60–90				Note 4
Off-Line Length (m) (ft)	0 0	140 450	83 270	270 890	300 990	320 1050	345 1130	Note 5
Platform Length[3] (m) (ft)	52 170	29 95	34 110	9 30	14 45	18 60	23 75	–
Assumed Vehicle Length (m) (ft)	N/A	N/A	N/A	4.6 15.0				3.0 10.0
Assumed Speed at Switch (m/s) (ft/s) (MPH)	N/A	7.6 25 17	7.6 25 17	11 37 25				9 29 20
Assumed Seating Policy	Standees Allowed	Standees Allowed	Standees Allowed	Standees Allowed				All Seated
Subjective Estimate of Ease of System Use[6]								
With 0 Transfers	++	+		–				+
With 1 Transfer	0	0		– –				N/A
With 2 Transfers	– –	– –		N/A				N/A

[1] The numbers for GRT stations refer to entrance queue, platform, and exit queue positions.

[2] For GRT stations assume the sum of passengers boarding and deboarding each vehicle is ten or less.

[3] For all-stop and skip-stop service assume the maximum link load = 10,000 passengers/hr and the linear passenger density is 0.3 passenger/m (1 passenger/ft). For skip-stop service assume a 35-second headway with every other train bypassing the simple off-line stations.

[4] The HCPRT station was not simulated but it should have somewhat higher vehicle throughput and less time lost per stop than a GRT station with the same number of queue and platform positions. This is because of shorter vehicle-movement times within the station due to higher acceleration and jerk limits, and because of fewer persons boarding and deboarding each vehicle.

[5] Off-line length depends on the number of queue and platform positions. With a 1.5 m (5 ft) vehicle separation in the queue and platform area (the same as assumed for the GRT station) a 4/2/2 station would be 150 m (490 ft) long, while a 9/5/6 station would be 205 m (670 ft) long.

[6] The rating scale from easy to difficult is ++, +, 0, –, – –.

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APPENDIX A

Structure of GRT Off-Line Station Simulation Model

The computer program used to determine the GRT-station throughputs listed in Table 3 models the flow of individual vehicles within one side of an off-line station with queues. The model also keeps track of individual passengers to determine their waiting time, but the spacial movement of passengers is not modeled. The program is written in FORTRAN IV and can be used on any CDC 6000 series computer.

The off-line station model is a discrete event-step simulator consisting of 16 routines. All changes in the status of the station are assumed to take place at the particular instants in time when events are executed. The model jumps directly from one event to the next, and simulation time is thus advanced in discrete intervals of variable length. The time of an event is determined from the occurrence of a previous event; i.e., the time a vehicle arrives at an entrance queue position is determined from the time the vehicle arrived at the station diverge switch. The events are stored in a simulation scheduler which is a time-ordered list of activities that are to occur during the simulation. An event is retrieved from the scheduler and the simulation time is updated to the time of the current event. As an event is being processed by the software, other events may be generated and stored in the scheduler. There are eight types of events in the model:

1) Stop Simulation
2) Party Arrival at Station
3) Vehicle or Empty Slot Arrival at Diverge Switch
4) Vehicle Arrival in Entrance Queue
5) Vehicle Arrival at Platform
6) Completion of Boarding
7) Possible Vehicle Departure from Exit Queue
8) Zero Out Data Buffers

The heart of the simulation model is the event list. A block of 200 computer words is reserved to store up to 50 events. The information needed to execute each event is stored in four computer words:

1) The simulation time when the event is to be executed.
2) The I.D. number of the vehicle involved in the event, if any.
3) The type of event (1 to 8).
4) The number of the event to be executed next, i.e., a pointer which links one pending event to the next.

A second key feature of the simulation model is the buffer which stores information on each queue and platform position. Two pieces of data are stored for each position:

- The status of the position

  0 = empty and available
  1 = empty but reserved
  2 = occupied and vehicle cannot move. This can only occur at the platform when vehicles are loading and unloading passengers.
  3 = occupied and vehicle is free to move

- The ID number of the vehicle which occupies that position or for which the position is reserved.

ID numbers are assigned to vehicles when they enter the station and are reassigned after they leave the station. This is done to save computer memory since the vehicle ID is used as a subscript to reference the vehicle's attributes The set of unused vehicle ID numbers is linked together by pointers.

Within the model, two types of data are maintained: data associated with a party and data associated with a vehicle. When a party arrives at the station its time of arrival, destination and number of passengers are noted. The party is then placed in a queue. As a vehicle becomes available at the platform, the appropriate party queue is emptied to the vehicle limit, party wait times and numbers in party are saved and the queue is advanced.

For each vehicle that enters the station, four times are saved. These are:

1) Vehicle arrival at diverge switch.
2) Vehicle arrival at the platform.
3) Vehicle arrival in the exit queue.
4) The time the vehicle starts its acceleration for merge onto the mainline.

All data is maintained internal to the model in named commons consisting of input data, constants, computed data constants, status data, and summary data.

APPENDIX B

Description of S&A Systems' GRT Off-Line Station-Simulation Model

In a parallel effort to the station model reported in Appendix A, S&A Systems of Dallas, Texas, developed a GRT off-line station simulation model which included a detailed representation of control system operation.

The computer model is a Monte Carlo, discrete event simulator. It is written in FORTRAN and utilizes the GASP system of simulation subroutines. Extensive input options and input parameters were designed to allow the definition and input of diverse control systems concepts and operating philosophies.

The model consists of a set of four interrelated programs which can be executed independently if desired. These are:

1) Deterministic Analysis Module
2) Single Station Simulation Module
3) Network Simulation Module
4) Passenger Flow Simulation Module

The deterministic analysis module performs a series of very detailed calculations relating to vehicle movement within the station and prepares a set of vehicle movement curves on a punched file for input into the single station simulation module. The station simulation module accepts this input, plus additional input describing vehicle movement characteristics relating to proximity of other vehicles in the system, i.e., speed separation profiles. The station simulation module simulates the movement of vehicles through the station, either a single-sided or a two-sided station with passenger boarding from a center platform between the guideways.

The single station module can be exercised independently or in conjunction with the passenger flow module. Operated independently, the station simulation module uses a fixed dwell time. The passenger flow module simulates in discrete fashion the movement of people from the station entrance, through the turnstiles, destination selector, escalators, wait areas, and onto the vehicle. When this module is operated with the station simulation module the dwell times become a function of the load time for the number of people available to be loaded onto the vehicle. The network simulation module is a future expansion module which has not yet been developed. The primary purpose of this module is to examine small networks of stations in such close proximity that they cannot truly operate in an idependent fashion.

The basic inputs to the deterministic module are the vehicle and station specifications and and absolute speed limits in various parts of the off-line guideway, called civil limit restrictions. These are used to move a vehicle through the station, making programmed stops at entrance queue positions, a station gate position, and exit queue positions as set by input data. The model moves the vehicle in small time increments (normally 0.1 second), keeping track at each instance of the phase of vehicle movement. As a vehicle is moved through the station, the program continually checks ahead for the next two speed limit constraints -- either of which could be a programmed stop or a transition from one civil speed limit to the next civil speed limit. The model projects ahead a stopping profile from its current position at each time point through each phase of movement to determine the point at which the vehicle will actually be required to start a maneuver to be stopped or to achieve the proper speed at the time the next constraint limit is reached. At the conclusion of a run of this module, a complete profile of vehicle movement through the station for the programmed set of station stops exists.

The single station module provides a discrete event simulation of vehicle movement through the station. Either a single-sided station or a two-way station with a common center platform can be run. The inputs to the model are the vehicle and station specifications, the starting and stopping profiles, and speed transition profiles as generated by the deterministic module plus an additional input which is the speed-separation curve. This speed-separation curve defines vehicle movement in relation to other vehicles in the system. This is a very important factor in station design since normally this curve will define the deceleration profile when a vehicle stops at the most upstream entrance queue position (i.e. a vehicle stopping in the most upstream queue position will decelerate following its separation curve rather than a normal stop curve and this requires a greater distance and more time to stop). The impact of this condition on station design is that the deceleration zone just upstream of the entrance queue should have its length determined by the vehicle follower curve as opposed to a calculation of the deceleration distance using the specified deceleration and jerk rates.

Also input to the station simulation module is the frequency of vehicles to be generated on the mainline, the percentage split into the station, the percent of vehicles loaded and empty, and the percent of passengers who will unload at this station. Working from these inputs, this module simulates the movement of vehicles as they enter the station, make any necessary stops in queuing positions, stop at the bay areas, perform a lateral docking maneuver if the docking option has been set, and then proceed out of the station. Vehicles exiting the station may have merge conflicts and be required to wait in the downstream queue area for a merge gap or slot. Statistics are kept on all vehicle stops and waiting times, dwell times, etc. The model actually moves vehicles through the station in small segments or blocks by establishing, from a set of curves or calculations, a velocity at the next block crossing point and a time to arrive at that point.

The passenger flow module simulates the movement of people and parties through the actual station from the station entrance to the point at which they board a vehicle. For those people unloading, the model simulates their movement from the point at which they unload down through the station to the station exit.